PCT WORLD INTELLECTUAL PROPERTY ORGANIZATION
International Bureau

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification [6] : G02B 6/16, 6/12

A2

(11) International Publication Number: WO 97/26571

(43) International Publication Date: 24 July 1997 (24.07.97)

(21) International Application Number: PCT/GB97/00128

(22) International Filing Date: 17 January 1997 (17.01.97)

(30) Priority Data:
96300394.2 18 January 1996 (18.01.96) EP
(34) Countries for which the regional or international application was filed: AT et al.

(71) Applicant *(for all designated States except US)*: BRITISH TELECOMMUNICATIONS PUBLIC LIMITED COMPANY [GB/GB]; 81 Newgate Street, London EC1A 7AJ (GB).

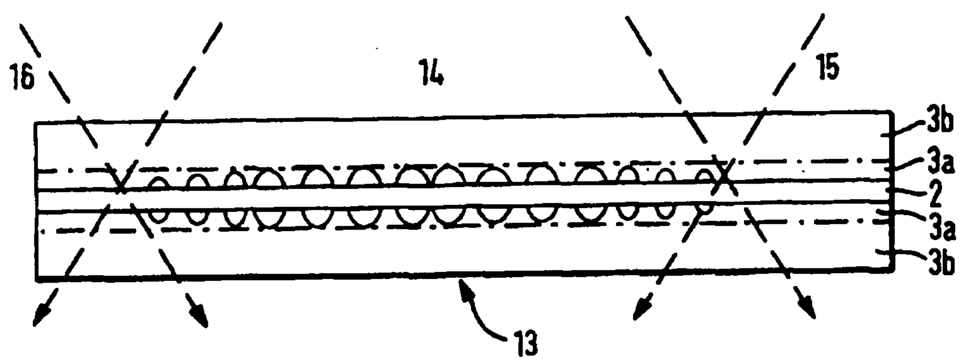
(72) Inventor; and
(75) Inventor/Applicant *(for US only)*: KASHYAP, Raman [GB/GB]; 79 Humber Ducy Lane, Ipswich, Suffolk IP4 3NU (GB).

(74) Agents: READ, Matthew, Charles et al.; Venner, Shipley & Co., 20 Little Britain, London EC1A 7DH (GB).

(81) Designated States: CA, JP, US, European patent (AT, BE, CH, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).

Published
Without international search report and to be republished upon receipt of that report.

(54) Title: OPTICAL WAVEGUIDE WITH PHOTOSENSITIVE REFRACTIVE INDEX CLADDING



(57) Abstract

An optical fibre (1) comprises a core (2) and a cladding (3) that includes an inner cladding region (3a) with a refractive index that is photosensitive to UV light, surrounded by a non-photosensitive outer cladding region (3b). Refractive index gratings can be written into the cladding region (3a). Also, the refractive index of the inner region (3a) can be altered by exposure to UV light to achieve mode matching at a splice between fibres with different core diameters. An optical fibre laser is disclosed with integral refractive index gratings (33, 34, 36) in the cladding of a fibre with an optically active core.

FOR THE PURPOSES OF INFORMATION ONLY

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

AM	Armenia	GB	United Kingdom	MW	Malawi
AT	Austria	GE	Georgia	MX	Mexico
AU	Australia	GN	Guinea	NE	Niger
BB	Barbados	GR	Greece	NL	Netherlands
BE	Belgium	HU	Hungary	NO	Norway
BF	Burkina Faso	IE	Ireland	NZ	New Zealand
BG	Bulgaria	IT	Italy	PL	Poland
BJ	Benin	JP	Japan	PT	Portugal
BR	Brazil	KE	Kenya	RO	Romania
BY	Belarus	KG	Kyrgystan	RU	Russian Federation
CA	Canada	KP	Democratic People's Republic of Korea	SD	Sudan
CF	Central African Republic			SE	Sweden
CG	Congo	KR	Republic of Korea	SG	Singapore
CH	Switzerland	KZ	Kazakhstan	SI	Slovenia
CI	Côte d'Ivoire	LI	Liechtenstein	SK	Slovakia
CM	Cameroon	LK	Sri Lanka	SN	Senegal
CN	China	LR	Liberia	SZ	Swaziland
CS	Czechoslovakia	LT	Lithuania	TD	Chad
CZ	Czech Republic	LU	Luxembourg	TG	Togo
DE	Germany	LV	Latvia	TJ	Tajikistan
DK	Denmark	MC	Monaco	TT	Trinidad and Tobago
EE	Estonia	MD	Republic of Moldova	UA	Ukraine
ES	Spain	MG	Madagascar	UG	Uganda
FI	Finland	ML	Mali	US	United States of America
FR	France	MN	Mongolia	UZ	Uzbekistan
GA	Gabon	MR	Mauritania	VN	Viet Nam

OPTICAL WAVEGUIDE WITH PHOTOSENSITIVE REFRACTIVE INDEX CLADDING

Field of the invention

This invention relates to an optical waveguide that has a photosensitive refractive index, and has particular but not exclusive application to optical fibres.

Background

It is well known that a germanium doped silica fibre exhibits photosensitivity, so that the refractive index of the core of the fibre changes when exposed to blue-green light, as demonstrated by Hill et al "Photosensitivity in Optical Waveguides; Application to Reflection Filter Fabrication" Applied Physics Letters Vol. 32 No. 10, 647 (1978). It was later shown that even stronger effects occurred if the core was exposed to ultra-violet radiation close to the absorption peak of a germania-related defect at a wavelength of 240 nm. Reference is directed to G. Meltz et al "Formation of Bragg Gratings in Optical Fibres by Transverse Holographic Method" Opt. Lett. Vol. 14, No. 15 823 (1989). The photosensitive phenomenon is not restricted to germania alone; cerium, europium and erbium: germanium have all shown varying degrees of sensitivity in a silica host optical fibre, but none has been as sensitive of germania. Germanium-boron co-doping has also proved highly successful producing large index modulations of the core, of the order of 10^{-3} and reference is directed to Y. Duval et al, "Correlation between Ultra-violet-induced Refractive Index Change and Photo-luminance is Ge-doped Fibre" Applied Physics Letters, Vol. 61, No. 25, 2955 (1992).

Furthermore, it has been reported that the photosensitivity can be enhanced by hot hydrogen treatment of optical fibres. Reference is directed to G. Meltz et al, "Bragg Grating Formation and Germanio Silicate Fibre Photosensitivity" International Workshop of Photo Induced Self-Organisation Effects in Optical Fibres SPIE Vol. 1516, p185 (1991).

Conventionally, optical fibres are formed by taking a glass tube and exposing the interior thereof to a dopant gas, so as to form a dopant deposit on the interior surface thereof. Thereafter, the glass tube is heated and sintered so as to collapse its interior with the result that the dopant forms a core region through the centre. The effect of the dopant is to raise the refractive index of the central or core region and leave a surrounding cladding region of the lower refractive index. The resulting, collapsed, glass tube is then drawn to produce a fine optical fibre, of reduced diameter ~ 120μm, with a core surrounded by cladding. In a conventional manner, the difference Δn between the refractive indices of the cladding n_1 and the core n_2 causes light to be guided along the core.

In conventional photosensitive optical fibres, i.e. fibres which have a photosensitive core, it is possible to record so-called refractive index Bragg gratings in the fibres and for a general review, reference is directed to "Photosensitive Optical Fibres: Devices and Applications" Kashyap et al, Optical Fibre Technology 1, 17-34 (1994). In a method described in EP-A-0 668 514, the cladding is rendered photosensitive as well as the core , so that the refractive index grating is recorded in both the core and, to an extent, in the cladding. Also, reference is directed to "Optical fiber design for strong gratings photoimprinting with radiation mode suppression" E. Delevaque et al, Conference on Fiber Communication, Technical Digest Series, Vol 8, No 6, pp 343-346, which discloses an optical fibre with a photosensitive core and a photosensitive intermediate region between the core and the cladding. A refractive index grating is written into the core and the intermediate region, which results in suppression of cladding modes. Photosensitive regions around the fibre core have also been used hitherto for mode matching, as described in US-A- 5,416 863

Refractive index gratings produced in optical fibres according to these prior recording methods can be used as narrow band reflective filters. One use of the reflective filter is to provide a fibre grating laser, as will now be

explained.

It is known that when the core of a silica optical fibre is doped with certain rare earth elements such as erbium or ytterbium, the fibre exhibits optical activity and can be used as an amplifier. The fibre is pumped with optical radiation at a first wavelength so that optical radiation at a second, different wavelength is amplified when passed through the pumped fibre. Such a rare earth doped fibre can be used to provide a laser. The rare earth doped fibre is included in an optical cavity, defined at one end by a refractive index fibre grating formed as aforesaid, spliced to the erbium doped fibre.

It would be desirable to write refractive index gratings in the rare earth doped fibre itself, but this has proved difficult in practice. When the fibre is doped with rare earth elements in its core, the fibres usually have little or no germania therein, so that it is difficult to write gratings in such highly doped fibres, although it has been demonstrated and reference is directed to G. Meltz et al *supra*. In order to write gratings in rare earth doped fibres, they typically need to be treated with hydrogen. Typically, the fibres are additionally doped with aluminium or phosphorous in order to raise the refractive index of the core. Such fibres exhibit photosensitivity in the core at a wavelength in the region of 193 nm but the photosensitivity is limited as compared with the photosensitivity for a germanium or boron doped core, which exhibits photosensitivity at 244 nm.

Summary of the invention

In accordance with the present invention from a first aspect, there is provided an optical waveguide including core and cladding regions for guiding optical radiation, the core including optically nonstative material and the cladding region including material with a photosensitive refractive index. As used herein, the term " optically nonstative material" means optically active material which can be excited into states for producing optical amplification or a lasing action, or optically non-linear material that has a refractive index

which varies transiently in a non-linear manner as a function of an applied electric ac or dc field or optical radiation e.g. but not limited to the Kerr effect, or poled material which has an electric dipole moment as a function of an applied electric field or optical radiation.

In accordance with the invention from a second aspect, the core of the waveguide includes material with a relatively non-photosensitive refractive index within a given wavelength range and the cladding region includes material with a relatively photosensitive refractive index within said wavelength range.

Thus, in accordance with the invention, a refractive index grating may be written in the cladding region of the optical waveguide even though the grating may be not written in the core region. It has been found that the transmission mode for radiation passing along the waveguide, extends sufficiently into the cladding region that a refractive index grating recorded therein, reflects the energy of optical radiation travelling along the waveguide, at an appropriate Bragg wavelength determined by the spatial periodicity of the refractive index grating.

In a further aspect, the invention provides an optical waveguide including core and cladding regions for guiding optical radiation, and a refractive index grating formed in the cladding region but not substantially in the core region.

The cladding material may include a cladding dopant which renders the refractive index of the cladding material photosensitive at least within a given wavelength range, and the core region may include a core dopant which renders the refractive index of the core material to be greater than that of the cladding material. Thus the photosensitivity characteristics of the cladding may be selected independently of the characteristics of the core.

The cladding dopant may include first and second different dopant materials

which render the cladding material photosensitive and which respectively reduce and increase the refractive index thereof as a function of dopant concentration, whereby in the absence of exposure to light in said wavelength range, the refractive index of the cladding assumes a base level less than that of the core material, and upon exposure to light in said wavelength range the refractive index of the exposed material of the cladding region changes from said base level.

The first and second dopant materials for the cladding material may comprise Be and Ge, permitting the cladding to be rendered photosensitive at 244 nm, and permitting the cladding to have a lower refractive index than the core, so as to allow single mode operation of the waveguide.

The core material may include a dopant such as a rare earth element to render it optically active, e.g. for use in an amplifier or a laser. The rare earth dopant may comprise Er or Yb or Nd.

For prior art fibres doped with rare earths in their core, an additional dopant such as Al or P is typically included in order to raise the refractive index relative to the cladding. The high value of refractive index produced in the core enables the core diameter to be reduced as compared with a conventional silica optical fibre, whilst permitting single mode transmission to be achieved. The difference between the core diameter of the erbium doped fibre and a conventional fibre, however gives rise to difficulties when it is desired to splice them together. In accordance with the invention, the fibre is provided with a photosensitive refractive index cladding region, so that the cladding can be exposed to optical radiation so as to reduce its refractive index, thereby causing the transmission mode of the rare earth doped fibre to spread into the cladding. As a result, the configuration of the transmission mode in the rare earth doped fibre can be caused to spread transversely so as to correspond to the transmission mode configuration of the conventional silica fibre, which has a larger diameter core. In this way, transmission mode matching can be

achieved.

The waveguides according to the invention may be spliced together and the core region of the waveguide according to the invention may have a transverse dimension which is less than the corresponding transverse dimension of the core region of the waveguide to which it is spliced, so that the alteration of the refractive index of the cladding material of the first waveguide spreads the mode of the first waveguide so as to correspond to that of the second waveguide.

The invention furthermore includes a splice when processed by this method.

The optical waveguide may comprise an optical fibre, such as a silica fibre, but may also comprise optical tracks on a substrate, defined by strips of photosensitive cladding material. The cladding material may be selectively exposed to optical radiation to change its refractive index so as to control optical connections between the tracks selectively.

Brief description of the drawings

In order that the invention may be more fully understood, embodiments thereof will now be described by way of example with reference to the accompanying drawings in which:

Figure 1 is a perspective view of a length of conventional optical fibre;

Figure 2a is a transverse sectional view of the fibre shown in Figure 1;

Figure 2b is a transverse section through a fibre in accordance with the invention;

Figure 3 is a graph of the refractive index profile through the conventional fibre in the section shown in Figure 2a;

Figure 4 is a graph of the refractive index profile through the optical fibre in accordance with the invention shown in Figure 2b;

Figure 5 is a graph corresponding to Figure 4 showing the variation of the refractive index in the photosensitive cladding of the optical fibre according to

the invention, showing the mode configuration for transmitted light;

Figure 6 is a schematic illustration of a refractive index recording method;

Figure 7 is an illustration of a grating recorded in an optical fibre according to the invention, by the method;

Figure 8 is a schematic illustration of a blazed refractive index grating; recorded in both the core and cladding of an optical fibre, according to the invention;

Figure 9 is a graph of the refractive index profile of the fibre shown in Figure 8, taken across a transverse section of the fibre;

Figure 10 is a schematic illustration of optical fibres spliced together, with different core diameters, with transmission mode configuration matching,

Figure 11a, b and c are graphs of the refractive index profiles and the corresponding transmission modes, taken across transverse sections A-A', B-B' and C-C' of the spliced fibre arrangement shown in Figure 10;

Figure 12 illustrates planar waveguides in accordance with the invention arranged in a matrix on a common substrate;

Figure 13 is a sectional view taken along D-D' shown in Figure 12;

Figure 14 is an illustration of the transverse refractive index profile of another example of an optical fibre in accordance with the invention;

Figure 15a illustrates an optical fibre laser that includes an optical fibre in accordance with the invention;

Figures 15b, c and d illustrate refractive index gratings formed in the fibre shown in Figure 15a;

Figure 16a is a graph of the wavelength response of the optical cavity shown in Figure 15a, in the absence of the blazed grating shown in Figure 15c,

Figure 16b is a graph of the wavelength response of the blazed grating shown in Figure 15c;

Figure 16c illustrates the wavelength response at the output of the laser shown in Figure 15a;

Figure 17 is a schematic perspective view of another embodiment of waveguide according to the invention; and

Figure 18 is a graph of the transmission lost as a function of wavelength for

light transmitted through a blazed grating as shown in Figure 8.

Detailed Description

Referring to Figure 1, this shows a conventional single mode optical fibre 1 made of silica which consists of a core region 2 doped so as to have a relatively high refractive index, surrounded by a cladding region 3 which has a relatively low refractive index. In a typical example, the core region 2 has a diameter of 8 - 10 μm and the cladding region 3 has an outer diameter of 125 μm. A transverse cross-section through the fibre is shown in Figure 2a and the corresponding variation in refractive index n in the direction *a*, across the diameter of the fibre, is shown in Figure 3. The graph of Figure 3 is somewhat idealised and illustrates a fibre with a refractive index n_1 in the cladding region and a refractive index n_2 in the region of the core. The value $\Delta n = n_2 - n_1$ is selected in order to cause optical radiation to be guided along the core, in a manner well known *per se*. Conventionally, the core region 2 may be doped with Al or P in a manner well known *per se*, in order to raise the value of n_2 relative to the refractive index n_1 of the surrounding silica cladding region 3. In a typical example of the prior art $n_1 = 1.454$ and $n_2 = 1.585$

If it is desired to write a refractive index grating in the fibre, a problem arises in that the Al or P doped core only exhibits a relatively low photosensitivity to ultra-violet light, at 193 nm, and hydrogen treatment may be required in order to achieve a desired level of photosensitivity. The core may alternatively be doped with Ge and/or B to achieve photosensitivity, which occurs at 244 nm. The effect of Ge dopant is to increase the refractive index of the core whereas the effect of B is to decrease the refractive index as a function of dopant density. Thus, it is possible to achieve co-doping so as to increase the photosensitivity without necessarily causing a substantial increase in overall refractive index.

Referring to Figure 3, the transmission mode configuration 4 for light

value for the fibre shown in Figure 4 can be the same or substantially similar to that of a conventional optical fibre, with the value of n_1 and n_2 being e.g. the same as shown in Figure 3. If desired, the photosensitivity of the cladding region can be enhanced by cold pressure hydrogen treatment as described in P. Lemaire, R. M. Atkins, V. Mizrahi and W. A. Reed, "High pressure H_2 loading as a technique for achieving ultrahigh UV photosensitivity and thermal sensitivity in GeO_2 doped optical fibres" Electron. Lett., vol 29, no. 13, 1191 (1993) and P. J. Lemaire, A. M. Vengsarkar, W. A. Reed, V. Mizrahi and K. S. Kranz, "Refractive index changes in optical fibres sensitised with molecular hydrogen" in Proc. Conference on Optical Fiber Communications, OFC '94, Technical Digest, p 47, paper TuL1, 1994.

The configuration shown in Figure 4 illustrates the situation in which the fibre according to the invention has not yet been exposed to ultra-violet radiation. Figure 5 shows the effect of incident ultra-violet radiation on the inner photosensitive cladding region 3a. Radiation at a wavelength of 244 nm causes the refractive index of the cladding region 3a to increase, as shown, to a value n_1' from the previous value of n_1, shown in dotted outline. The difference $\Delta n'$ between the refractive index n_2 and n_1' that occurs after the u.v. exposure still permits guiding of light along the waveguide. The transmission mode configuration prior to exposure to u.v. light is shown in dotted outline 4 and corresponds to the prior art mode configuration shown in Figure 3. The effect of the increase in n_1 due to the u.v exposure results in a spreading of the mode configuration into the cladding so as to produce mode configuration 5 with tails 5a, 5b which spread into the photosensitive cladding region 3a. In an example of the invention, the core 2 had an outer diameter of 10μm, the region 3a had an outer diameter of 20 μm, and the region 3b of the cladding had an outer diameter of 125 μm. The refractive index of the core n_2 was 1.475, and the refractive index n_1 of the cladding prior to u.v. exposure was 1.454. After exposure, the value of the refractive index of the inner cladding region 3a changed to $n_1' = 1.464$.

The photosensitivity of the cladding 3 can be used to achieve a number of different effects. A refractive index grating can be recorded in the cladding, with the refractive index varying between values n_1 and n_1' with a spatial periodicity Λ along the length of the cladding. It has been found that because the tails 4b, 5b of the transmission mode configuration extend into the cladding, the mode interacts sufficiently with the spatial refractive index variations to produce Bragg reflection. The wavelength of the Bragg reflection is given by $\lambda_{Bragg} = 2\ \Lambda n_{eff}/N$, where Λ is the period of the interference pattern and n_{eff} is the effective index of the guided mode. N is an integer and indicates the order of the interaction. In this case $n_{eff} \sim (n_2+n_1)/2$.

The refractive index grating may be written in the fibre by any of a number of conventional techniques and for a general review, reference is directed Kashyap *supra*. One example will now be described with reference to Figure 6 and 7. Ultra-violet light from a laser 6 at a wavelength of 244 nm is directed through a beam splitter 7 to form first and second coherent beams 8, 9 that are reflected by mirrors 10, 11, so as to interfere with one another and form an interference pattern in region 12 extending transversely along the length of an optical fibre 13 that has a photosensitive cladding as described with reference to Figures 4 and 5. As shown in more detail in Figure 7, the interference pattern becomes recorded in the photosensitive cladding 3 of the fibre 13 with the result that a spatially periodic refractive index variation is produced in the cladding with a spatial periodicity Λ. The amplitude of the variation may vary from a peak in a central region 14 of the pattern and decrease towards the ends 15, 16 thereof. The pattern is not recorded in the core 2 of the fibre to any significant extent due to the fact that the core, typically doped with Al or P and optionally a rare earth element such as Yb or Er, is not substantially photosensitive to the incident light of wavelength 244 nm.

The fibre with its photosensitive inner cladding region may be manufactured by one of a number of conventional fabrication techniques. Generally, a

preform is produced with the desired refractive index profile, which is then drawn to produce the fine fibre. Several methods can be used for the preform fabrication. The three commonly used methods are modified chemical vapour deposition (MCVD), outside vapour deposition (OVD) and vapour-phase axial deposition (VAD). Among the three, MCVD is the most widely employed and for a detailed review, reference is directed to Fundamentals of Fibre Optics in Telecommunications and Sensor Systems, editor P. B. Pal, Wiley Eastern Limited - Fabrication Techniques of Optical Fibres, H. Karstensen Ch. 9, pp 223-248.

An example of fabrication of the preform, using MCVD will now be described. For a detailed description of the apparatus used, reference is directed to Karstensen *supra* pp 233-239. Firstly, controlled amounts of $SiCl_4$ vapour as dopant, along with oxygen are fed into a rotating fused silica substrate tube. A traversing oxy-hydrogen burner heats a short zone of the tube to a temperature of about 1600°C. In this hot zone, the chemicals react forming glass particles which are subsequently deposited downstream on the inner wall of the tube. The heat from the slowly traversing burner which follows, sinters the deposited soot to form a transparent glass layer. The burner is then quickly returned to the other end of the tube and the process repeated so as to build up layers of material which eventually will form the exterior cladding region 3b of the previously described fibre in accordance with the invention.

Thereafter, dopant gases are introduced into the process and a mixture of P and F are introduced as dopants in successive layers. The effect of the P and F is respectively to increase and decrease the refractive index, and overall to reduce the melting point of the glass deposited.

Then, a mixture of gaseous BCl_3 and $GeCl_4$ is fed into the substrate tube, together with $SiCl_4$, so as to deposit glass which is co-doped with B and Ge. The resulting glass eventually forms the inner cladding layer 3a and has a

refractive index which is the same as the outer cladding layer and is also photosensitive to u.v. light.

Thereafter, in order to form material for the fibre core, the flow rate of $GeCl_4$ is increased relative to BCl_3, whilst maintaining the flow rate of $SiCl_4$ the same. This deposits glass material with a higher refractive index than that of the cladding. If desired, Er dopant or similar rare earth materials can be introduced in order to render the eventual fibre core optically active.

The resulting structure is then sintered, so as to collapse the tube and produce the preform, from which the fibre can be drawn by conventional techniques.

Another application of the invention concerns radiation mode taps, also known as a side-tap filters. These can be formed by writing a slanted or so-called blazed grating into the core of the fibre. The grating couples light travelling along the fibre into a radiation mode, in which light is no longer guided in the core. Reference is directed to G. Meltz et al "In-Fibre Bragg Grating Tap" Proc. Conference on Optical Fibre Communications, OFC '90, Technical Digest p 24, paper TUG1, 1990. As described in this reference, blazed gratings written into a fibre result in outcoupling of light at visible wavelengths. By increasing the diameter of the core locally so as to provide a weakly guiding fibre, it is possible easily to overcome mode confinement due to the guidance of the fibre, over much narrower bandwidths, in order to produce the desired outcoupling of light from the fibre. However, there is a limitation to the narrowness of the band that can be produced. The present invention provides an alternative solution to increasing the core diameter locally.

Referring now to Figure 8, there is shown an optical fibre 16 made of silica, with a core 17 and a surrounding cladding 18. The core is non-photosensitive and optically active, and the cladding is photosensitive, the fibre having been formed in the manner described with reference to Figure 4.

A blazed refractive index grating 19 shown schematically, is written into the photosensitive cladding 18 of the fibre 16 in a manner known *per se* and described by Meltz et al *supra*. The core may be doped with Al or P and the cladding can be co-doped with Ge and B to provide photosensitivity as previously described. A plot of refractive index n across the diameter of the fibre in direction *a* is shown in Figure 9. The refractive index grating 19 is thus recorded substantially only in the cladding 18. The mode of light transmitted along the fibre 16 becomes enlarged beyond the core into the cladding and it can be shown that this produces a narrowing in the bandwidth of the filter characteristics. In one specific example, the fibre had a core diameter of 12μm and an external cladding diameter of 125μm giving a side tap bandwidth of approximately 15 nm at 1550 nm. It will be appreciated that conventional type-B fibres have a core diameter of the order of 8μm so that the side tap filter can readily be spliced to conventional fibres without significant mode loss. Whilst in Figure 8, the entire cladding is photosensitive, the cladding may in an alternative configuration, be formed as a photosensitive inner cladding, co-doped with Ge:B, matched to the refractive index of an outer cladding which is not photosensitive, as previously described with reference to Figure 2b. A graph of the transmission loss obtained along a length of fibre, with a grating as shown in Figure 8, as a function of wavelength is shown in Figure 17.

As an alternative, unblazed long period gratings as described by A. N. Vengsarkar et al, "Long Period Fibre Gratings as Band Rejection Filters" OFC 95 paper PD4 San Diego California 1995, could be formed by this technique.

The invention also has application to mode matching spliced fibres. For fibres with erbium doped cores, the core may be doped additionally with Al to achieve a high refractive index, in which case the core diameter can be reduced substantially whilst still transmitting in the single mode. Thus, the core diameter can be reduced to values such as 4μm due to the increase in Δn between the core and the cladding resulting from the high dopant

concentration in the core. Whilst such an arrangement is optically efficient, difficulties arise in splicing such a fibre, with a small diameter core, to a conventional fibre or a fibre as described with reference to Figure 8, which includes a blazed grating, or to a conventional side tap filter which includes a blazed grating in a relatively weakly guiding fibre having an enlarged core diameter as described previously.

Figure 10 shows a configuration which overcomes this problem. A first silica fibre 20 has a non-photosensitive Er doped core 21 surrounded by cladding material 22, which includes an inner photosensitive cladding region 22a surrounded by a non-photosensitive region 22b. The core 21 may additionally be doped with Al in order to increase its refractive index. As a result, the fibre is strongly guiding and the core diameter w_1 may be of a relatively small value e.g. 4μm. The surrounding photosensitive cladding region 22a may be doped with Ge and Be as previously described with reference to Figures 4 and 5, and may have an external diameter a_c of 16μm.

The fibre 20 is spliced at S to a silica based fibre 23 that has a core 24 surrounded by cladding 25. The fibre 23 may be a conventional standard fibre as used in optical telecommunication system with a core diameter w_2 of 8μm, i.e. significantly larger than the core diameter of fibre 20. The external diameter a_2 of the cladding 25 may be of a similar dimension to that of the fibre 22 of the order of 120μm. However, as an alternative, the fibre 23 may have an enlarged core and include a blazed grating or may be as shown in Figure 8.

Referring now to the graphs shown in Figures 11a, b and c, the refractive index distribution across a transverse section of the fibre is shown for corresponding sections A-A', B-B' and C-C' respectively in Figure 10. Considering Figure 11a, it can be seen that the value of the refractive index of the core n_2 has a relatively high value in the Er:Al doped core region 21, whereas the photosensitive Ge:B cladding region 22a has not been exposed to

u.v. radiation a relatively low refractive index n_1 corresponding to the refractive idea of the surrounding cladding region 22b.

Referring to Figure 11c, the core of the standard fibre 23 has a lower refractive index n_2'' than the core of the fibre 20, and the core of fibre 23 has a larger diameter w_2 than the diameter w_1 of the core of fibre 20.

Referring to Figure 11a again, the transmission mode configuration is shown at 26 and it will be seen that the mode has a relatively narrow configuration (as compared with Figure 11c) with a relatively sharp peak 26a and relatively small tail 26b, which extends into the cladding. In contrast, in Figure 11c, it can be seen that the transmission mode, shown at 27, is generally wider with a lower peak, 27a than the corresponding peak 26a in fibre 20. The difference between these two mode configurations can give rise to significant losses at the splice S between the two fibres.

In accordance with the invention, the splice is exposed to u.v. radiation so as to change the refractive index of the photosensitive cladding region 22a of fibre 20, in the region of the splice. In one specific example, the splice is exposed to radiation at 244 nm from a laser source (not shown) in order to alter the refractive index of the photosensitive Ge:B co-doped region 22a. This is shown in more detail in Figure 11b from which it can be seen that the refractive index of the cladding 22 has altered from value n_1 (Figure 11a) to n_1'. The mode configuration 28, becomes wider and spreads out into the region of the cladding 22, as a result of the fibre becoming more weakly guiding to the mode, due to the decrease in value $\Delta n = n_2 - n_1'$, as compared with the configuration in Figure 11a. Thus, in the region of the splice, the mode can spread out as shown in Figure 11b, in the fibre 20 in order to correspond to the width of the mode configuration for fibre 23, shown in Figure 11c. In this way, losses at the splice S are avoided. The progressive spreading of the mode is illustrated by lines 29 in Figure 10. It will be understood that as an alternative, the value of the term Δn can be configured

to increase. This has the effect of decreasing the width of the mode configuration for fibre 23. This can be useful in certain matching situations where it is necessary to reduce the diameter of the mode.

Whilst the invention has been described hitherto in connection with optical fibres, it has application to other waveguides that have a core region of a first refractive index and a surrounding cladding region of a second different refractive index, configured to produce guiding of optical radiation. Figures 12 and 13 show an alternative configuration in which the waveguides consist of tracks on a substrate. A silica, optically transparent substrate 30 is doped on its upper surface with Ge:B through a mask (not shown) to provide a rectangular matrix pattern of optically conductive tracks 31, arranged in rows and columns C_n, R_n. The refractive index difference Δn between the tracks 31, the underlying glass substrate 30 and the overlying air, produces guiding of light along the rows and columns. Selective connection and disconnection between intersecting rows and columns can be achieved by exposing the substrate selectively to ultra-violet radiation. For example, when it is desired to disconnect the connection between row R_1 and column C_1, u.v. radiation at 244 nm is directed onto the substrate transversely e.g. from a laser source in order to expose selectively region 32. In this way, the refractive index of the photosensitive layer 32 in the region of the intersection of the row and column, is raised to a sufficient level that the cladding material 31 not longer acts as a guide and light is dissipated in region 32, when travelling along the row R_1 or column C_1. The device shown in Figure 12 can thus be used as a programmable logic array for optical signals.

Referring now to Figure 14, another example of an optical fibre in accordance with the invention is shown, which can be considered as a modification of the configuration shown in Figure 4 and like regions are marked with the same reference numbers. The silica fibre consists of a core 2 with a cladding 3 having an inner cladding region 3a which is photosensitive as a result of being co-doped with B:Ge in the manner described previously. The region 3a in the

absence of exposure to u.v. light has a refractive index which corresponds to that of the outer cladding region 3b, which is not doped to be photosensitive. In the fibres previously described, the core may be doped with Al or P in order to raise its refractive index. The core may alternatively be doped with Ge and/or B to achieve photosensitivity. However, this cannot be achieved if it is desired to dope the core with Yb or Er in order to achieve optical activity, because as previously described, it is not possible to use Ge or B in combination with a rare earth dopant in order to achieve photosensitivity in the core. The arrangement of Figure 14 provides a solution to this problem.

In Figure 14, the core 2 is arranged as an inner core region 2a surrounded by an outer core region 2b. The inner core region 2a may be doped with a rare earth element such as Er or Yb and may additionally include Al to raise the refractive index further. The outer core region 2b is doped with Ge and/or B so as to be photosensitive. Thus, with this arrangement, refractive index gratings may be written in both the inner region 3a of the cladding and the outer region 2b of the core.

Referring now to Figures 15 and 16, an optical fibre laser is shown, in which a resonant cavity is formed between first and second refractive index gratings 33, 34 formed in an optical fibre 35. The fibre corresponds to fibre 1 shown in Figure 2b and has a core 2 surrounded by a photosensitive inner cladding region 3a, and a non-photosensitive outer cladding region 3b. The gratings 33, 34 are shown in more detail in Figures 15b and 15d respectively. Grating patterns g1 and g2 are recorded in the inner cladding regions 3a in a manner described previously with reference to Figure 7 or in any of the other well known methods e.g. described in Kashyap et al *supra*. The core of the fibre 35 is doped with a rare earth element such as Yb or Er so as to render it optically active. The core 2 is non-photosensitive.

The fibre 35 also includes a blazed grating which has a lossy wavelength characteristic which is shown in more detail in Figure 16b. The blazed

grating 36 is shown in more detail in Figure 15c and includes a blazed refractive index pattern g3 recorded in the inner cladding region 3a of the fibre, but not substantially in the core or the outer cladding region.

The fibre is pumped by laser radiation at 1480 nm (or 980 nm) from a pump laser 38 connected through a conventional fused fibre coupler 39 to the fibre 35.

The gratings 33, 34 have a spatial periodicity chosen to produce resonance for signals fed from a laser 40 into the fibre. The nominal operating wavelength of laser 40 in this example is 1530 nm. The wavelength characteristic of the cavity, in the absence of the blazed grating 36 is shown in Figure 16a and it will be seen that the characteristic includes an undesirable peak at the centre wavelength of laser 40, namely 1530 nm. The characteristics of the blazed grating 36 are selected so its lossy peak is 1530 nm so that the effect of the filter is to suppress the gain peak shown in Figure 16a. The resulting output at end 41 of the fibre is shown Figure 16c, from which it can be seen that the blazed grating 36 suppresses the peak that otherwise would occur at 1530 nm.

It will be seen that the gratings shown in Figure 15a are all recorded in the optically active fibre. The gratings can be recorded in the inner cladding region 3a, with the result that there are no splices. In contrast, in the prior art, the optically active fibre needed to be spliced to conventional germano-silicate fibres because it was not possible easily to record that the gratings in the optically active fibre itself.

The optical activity of the core region of the fibres according to the invention need not necessarily be produced by dopants. For example, as shown in Figure 18, the fibre may comprise a tubular member 42 made of Ge:B doped silica glass, which provides the photosensitive cladding region, filled with an optically nonstative liquid or colloid 43, which provides the core region. A refractive index gating may be recorded in the cladding region 42, in the

manner described with reference to Figure 6. More details of this hollow fibre construction can be found in our PCT/GB95/02322. Examples of nonstative materials which can be used to form the core 43 are liquid crystals which exhibit a variable refractive index as a function of an applied electric field, liquids which exhibit the Kerr effect, nitrobenzene and colloidal suspensions of quantum dots. The Ge doping in the glass tube 42 may be a radially inner region only, as indicated by the dotted line 44, in a similar fashion to that described with reference to Figures 2 and 4.

Many other modifications and variations fall within the scope of the invention. For example the core region may include nonstative poled material which exhibits a dipole moment, which is responsive to an applied electric field. Reference is directed to L. Li & D. N. Payne "Permanently-Induced Linear Electro-Optic Effect in Silica Optical Fibres, Dig. Conf. Integrated and Guided Wave Optics, 1989 OSA, Paper TuAA2-1 (1989) and T. Fujiwara, D.Wong, Y. Zhao, S. Fleming, V. Grishina & S. Poole, "UV-Excited Poling and Electrically Tunable Bragg Gratings in a Germanosilicate Fibre", Postdeadline Paper OFC '95 (Feb '95). The fibre may be provided with an electrode arrangement to apply an electric field to the poled material in the core region to control its optical characteristics. Reference is directed to EP 96300638.2.

In another modification, the cladding region includes concentric regions of photosensitive material spaced by concentric regions relatively low photosensitivity.

As used herein, the term optical radiation includes both visible and non-visible radiation including infra-red and ultra-violet radiation.

Claims

1. An optical waveguide (1, 30) including core (2, 31) and cladding regions (3, 32) for guiding optical radiation, the core including optically nonstative material and the cladding region including material with a photosensitive refractive index.

2. An optical waveguide (1, 30) including core (2, 31) and cladding regions (3, 32) for guiding optical radiation, the core including material with a relatively non-photosensitive refractive index within a given wavelength range and the cladding region including material with a relatively photosensitive refractive index within said wavelength range.

3. An optical waveguide according to claim 1 or 2 wherein the cladding material includes a cladding dopant which renders the refractive index of the cladding material photosensitive at least within a given wavelength range, and the core region includes material with a core dopant which renders the refractive index of the core material to be greater than that of the cladding material.

4. An optical waveguide according to claim 3 wherein the cladding dopant includes first and second different dopant materials which render the cladding material photosensitive and which respectively reduce and increase the refractive index thereof, whereby in the absence of exposure to light in said wavelength range, the refractive index of the cladding assumes a base level less than that of the core material, and upon exposure to light in said wavelength range the refractive index of the exposed material of the cladding region changes from said base level.

5. An optical waveguide according to claim 4 wherein the refractive index of the photosensitive cladding region increases or decreases when exposed to light in said wavelength range.

6. An optical waveguide according to claim 4 wherein the first and second dopant materials for the cladding material comprise B and Ge.

7. An optical waveguide according to any one of claims 3 to 6 wherein the core dopant comprises Al or P.

8. An optical waveguide according to any preceding claim wherein the core material includes a dopant for rendering the core optically active.

9. An optical waveguide according to claim 8 wherein the dopant for producing the optical activity comprises a rare earth dopant

10. An optical waveguide according to claim 9 wherein the rare earth dopant comprises Yb or Er.

11. An optical waveguide according to any preceding claim wherein the cladding (3) includes a first relatively photosensitive region (3a) and a second relatively non-photosensitive region (3b).

12. An optical waveguide according to claim 11 wherein the first and second regions (3a, 3b) have the same refractive index prior to exposure of the first region (3a) to light to which it is photosensitive.

13. An optical waveguide according to any preceding claim wherein the core and cladding material comprises silica glass.

14. An optical waveguide according to any preceding claim including a refractive index grating formed in the cladding region.

15. An optical waveguide (1, 30) including core (2, 31) and cladding regions (3, 32) for guiding optical radiation, and a refractive index grating formed in the cladding region but not substantially in the core region.

16. An optical waveguide according to claim 14 or 15 wherein the grating is a blazed grating (19).

17. An optical waveguide according to any preceding claim wherein the core (2) includes an inner region (2a) which is relatively non-photosensitive to light at a given wavelength, surrounded by an outer region which is relatively photosensitive to light at said given wavelength.

18. An optical waveguide according to any one of claims 1 to 6 wherein the material of the core region includes an optically active liquid.

19. An optical waveguide according to claim 18 wherein the optically active liquid comprises nitrobenzene

20. An optical waveguide according to claim 18 wherein the optically active liquid comprises liquid crystal material.

21. An optical waveguide according to any preceding claim, comprising an optical fibre (1).

22. An optical amplifier including an optical waveguide (35) as claimed in any preceding claim, with a refractive index grating (33, 34, 36) formed in the cladding region (3a) thereof.

23. An amplifier according to claim 22 wherein the grating (33, 34) forms part of a resonant cavity for producing lasing amplification.

24. An amplifier according to claim 23 including a blazed refractive index grating in the cladding region of the waveguide for modifying the wavelength resonant characteristic of the cavity.

25. A method of mode matching first and second optical waveguides (20,

23) each including core (21, 24) and cladding regions (22, 25) for guiding optical radiation in a respective transmission mode configuration (26, 27, 28), the first waveguide being as claimed in any preceding claim, the method including exposing the cladding material (22) of the first fibre to optical radiation so as to alter its refractive index and thereby match the transmission mode configuration (28) of the first waveguide (20) to that (27) of the second waveguide (23).

26. A method according to claim 25 wherein the first and second waveguides are spliced together and the core region (21) of the first waveguide has a transverse dimension (w_1) which is less than the corresponding transverse dimension (w_2) of the core region of the second waveguide (23), wherein the alteration of the refractive index of the cladding material of the first waveguide spreads the mode of the first waveguide to correspond to that of the second waveguide.

27. Spliced waveguides (20, 23), mode matched by a method as claimed in claim 25 or 26.

28. Spliced waveguides according to claim 26 or 27 wherein the second waveguide includes a refractive index grating.

29. Spliced waveguides according to claim 28 wherein the grating in the second waveguide is a blazed grating.

30. An optical waveguide according to any one of claims 1 to 20 including a substrate (30) overlaid by photosensitive cladding material (31) disposed in a track (R_n, C_n).

31. An optical waveguide according to claim 30 including a plurality of tracks disposed in a matrix, on the substrate

32. A method of forming selective connection of said tracks in a waveguide as claimed in claim 32, including selectively exposing the cladding to optical radiation which alters the refractive index thereof.

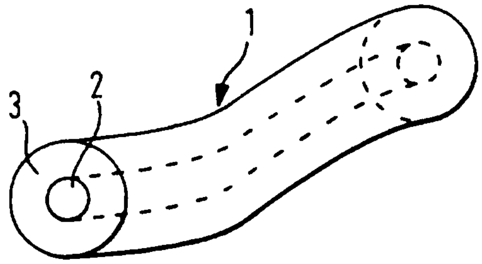


FIG. 1
(PRIOR ART)

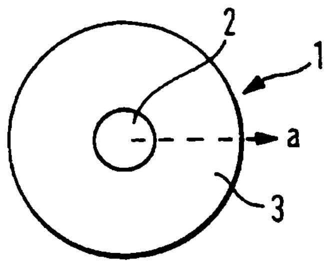


FIG. 2a
(PRIOR ART)

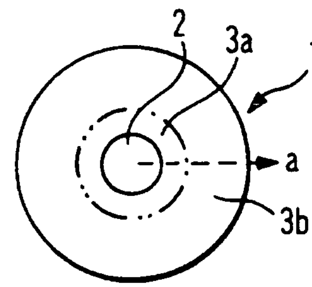


FIG. 2b

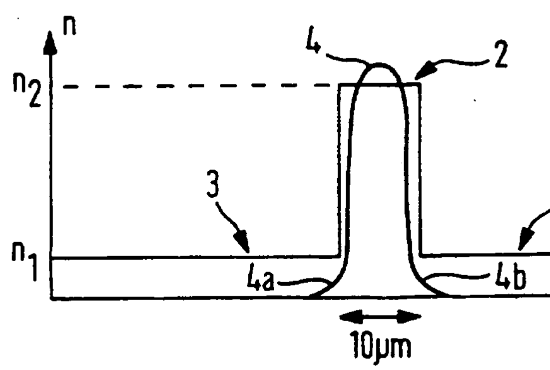


FIG. 3
(PRIOR ART)

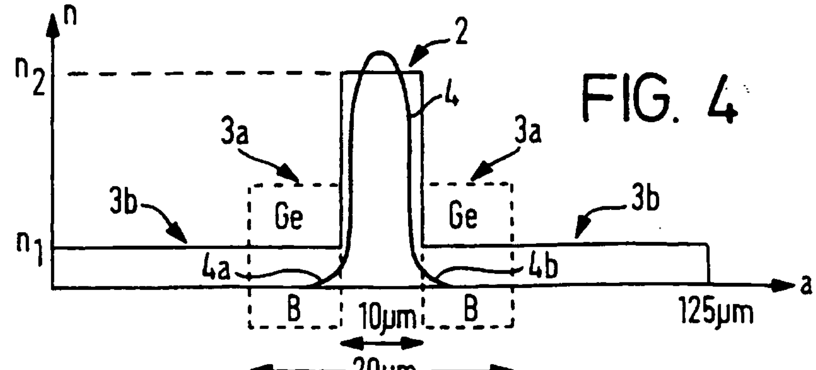


FIG. 4

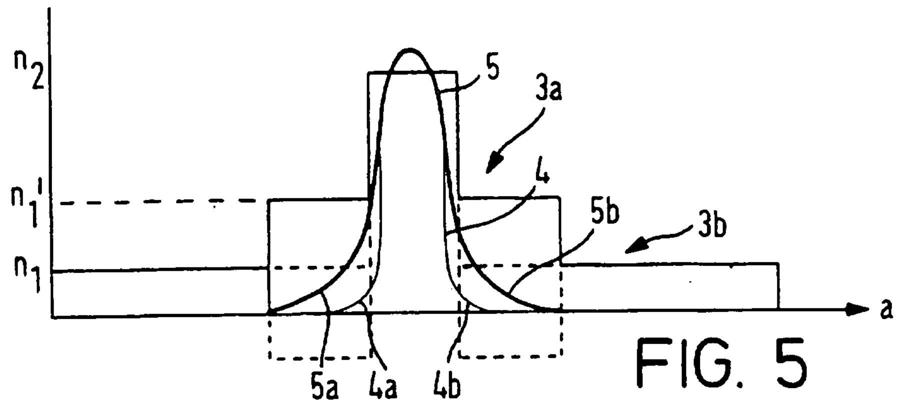


FIG. 5

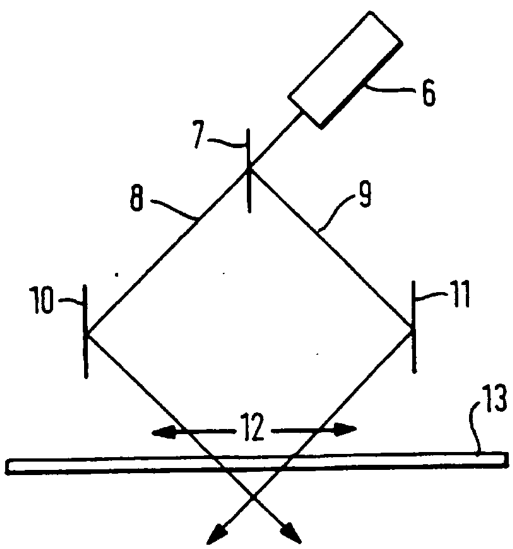


FIG. 6

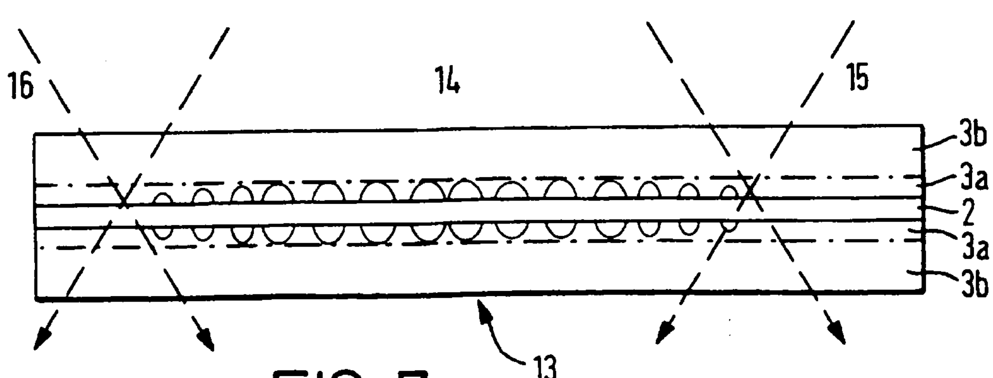


FIG. 7

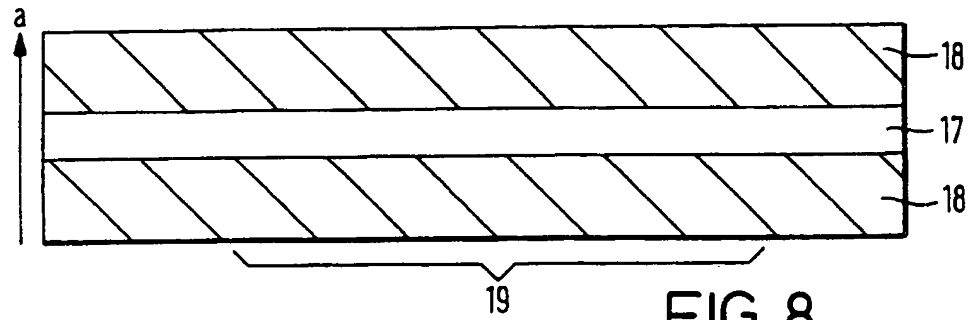


FIG. 8

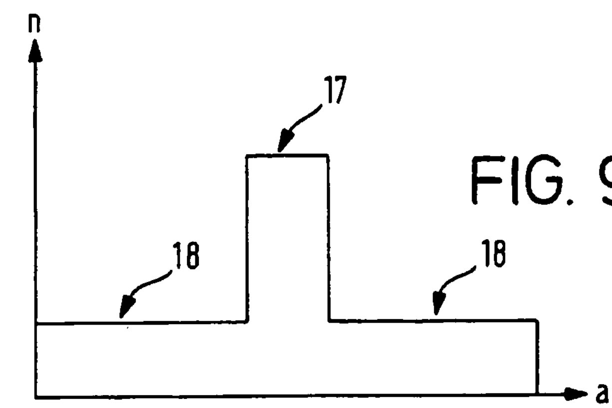


FIG. 9

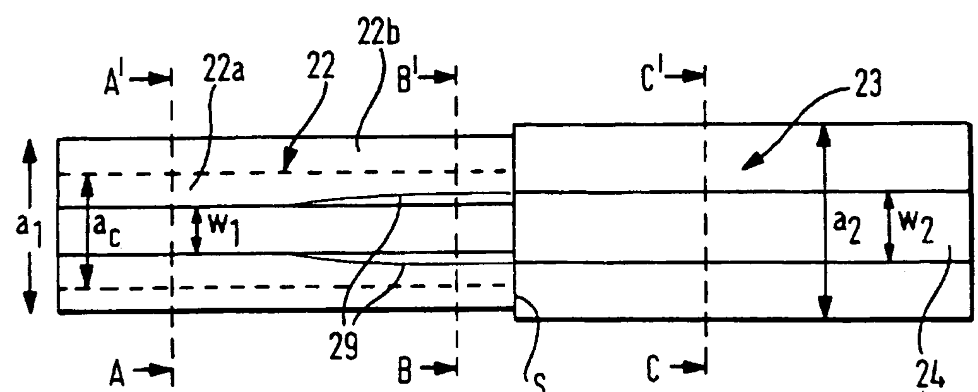


FIG. 10

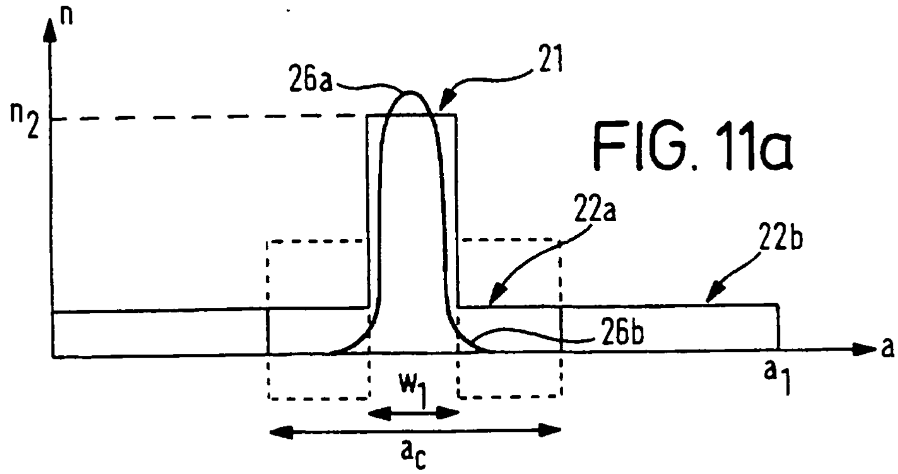


FIG. 11a

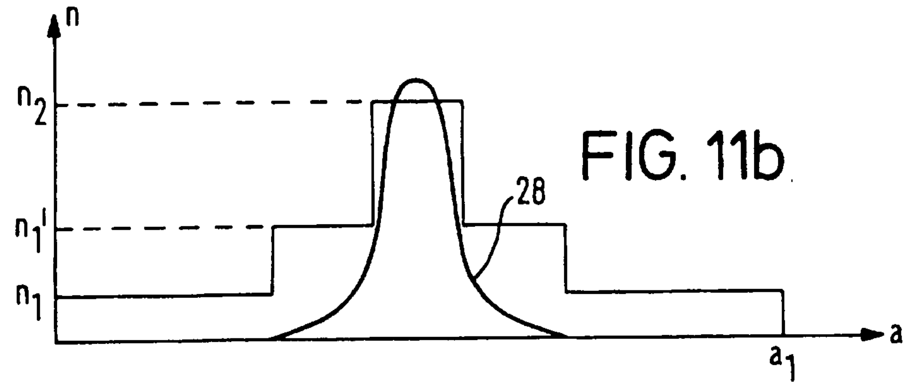


FIG. 11b

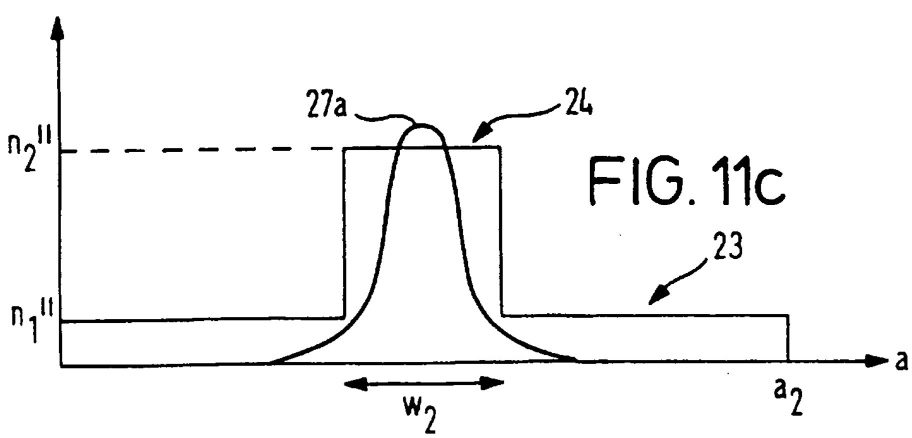


FIG. 11c

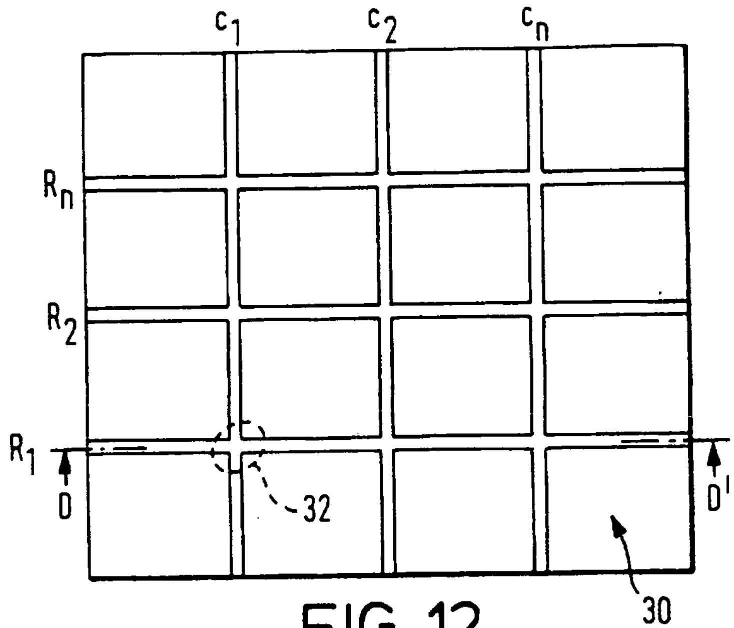


FIG. 12

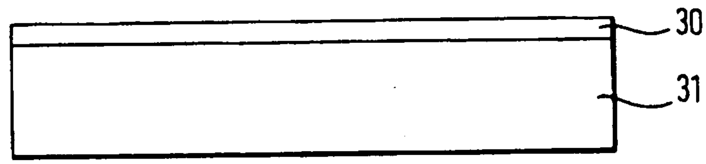


FIG. 13

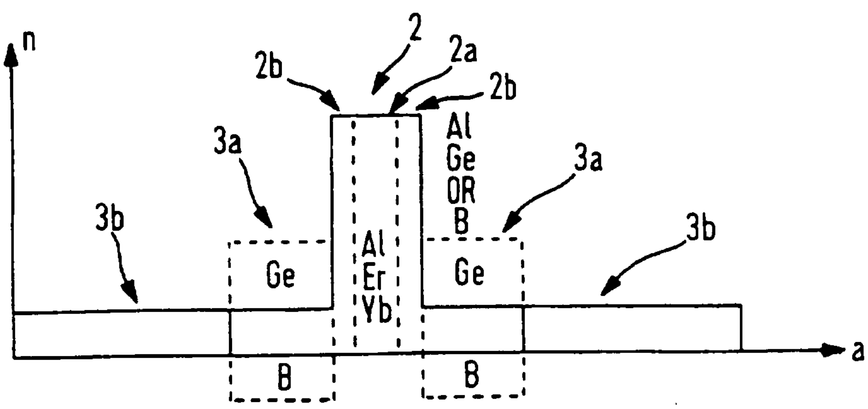


FIG. 14

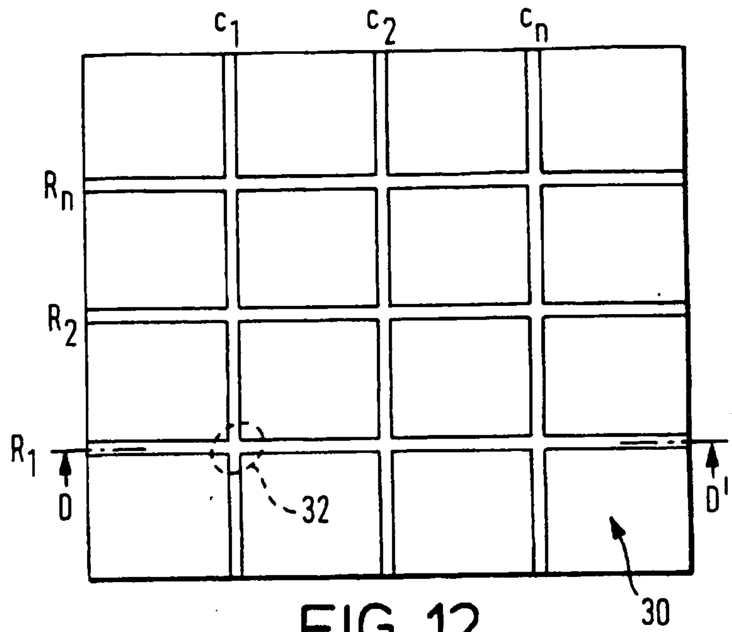


FIG. 12

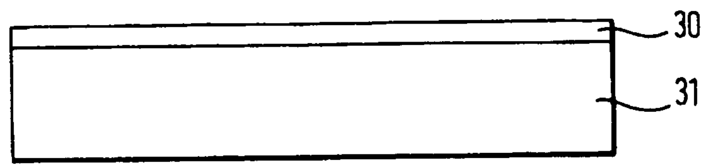


FIG. 13

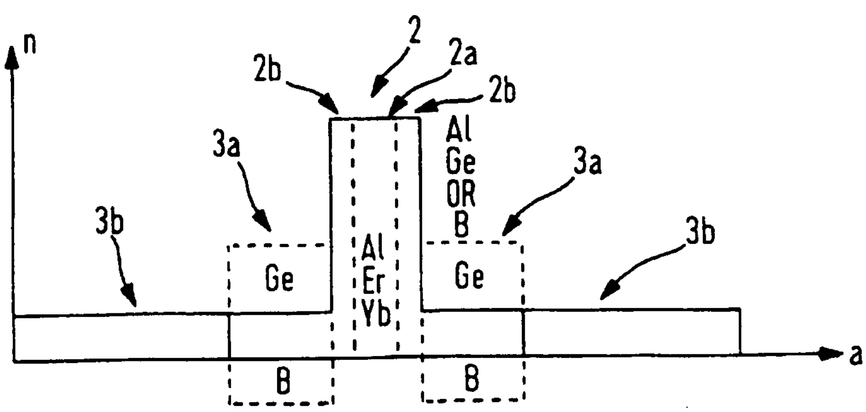


FIG. 14

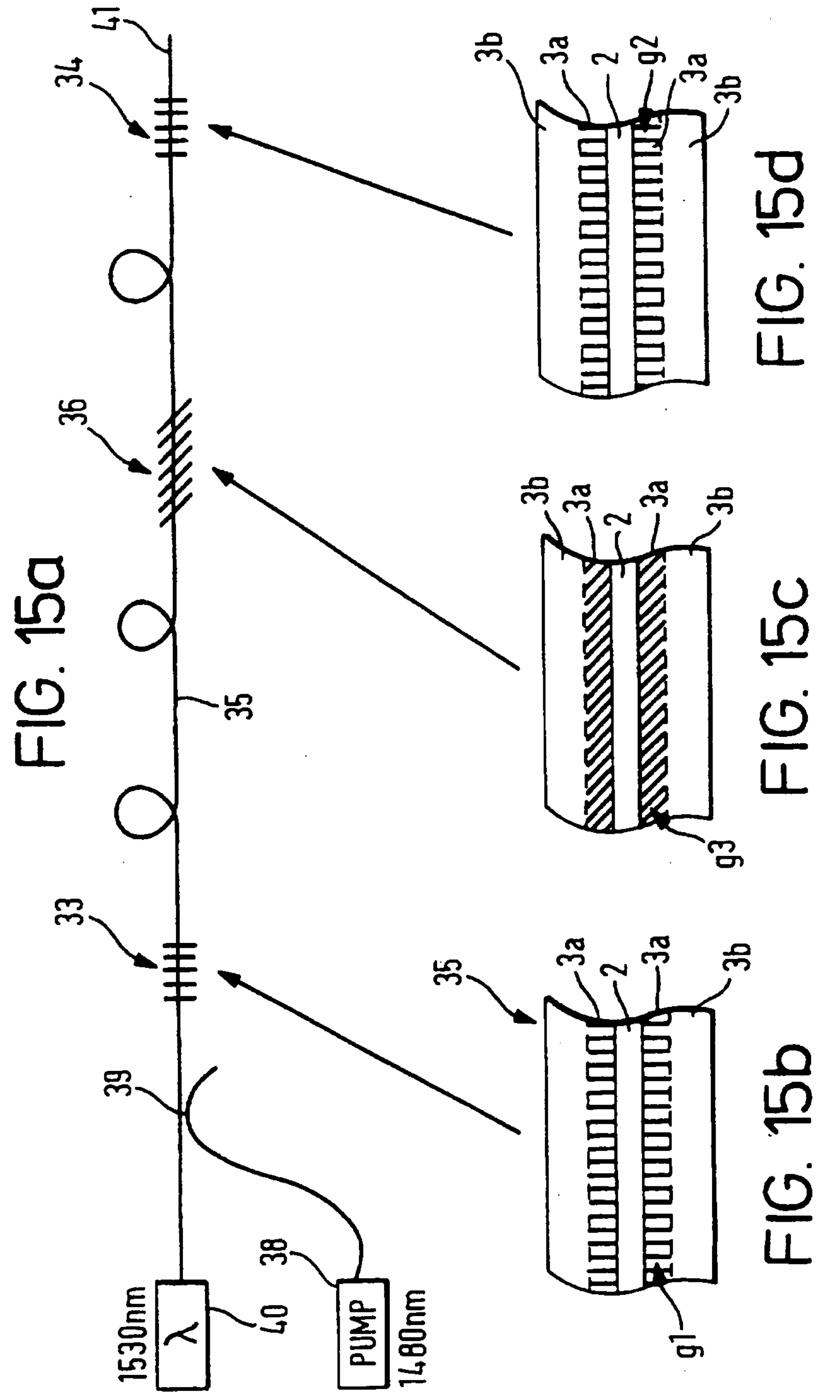


FIG. 15a

FIG. 15b

FIG. 15c

FIG. 15d

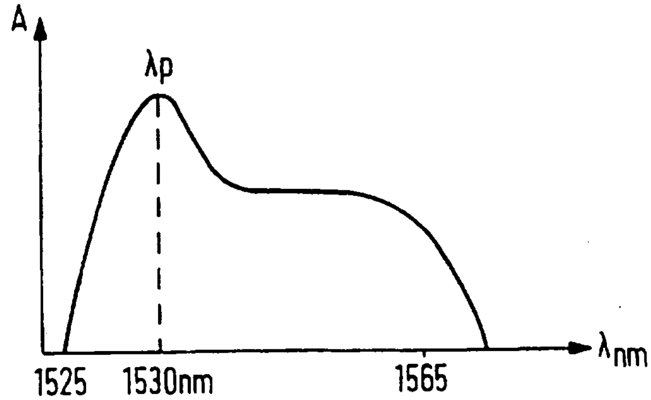


FIG. 16a

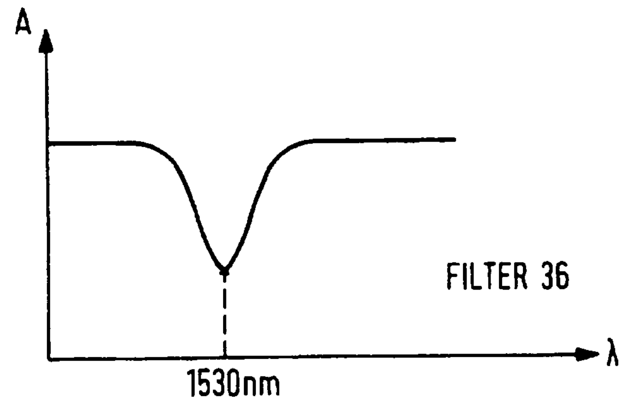


FIG. 16b

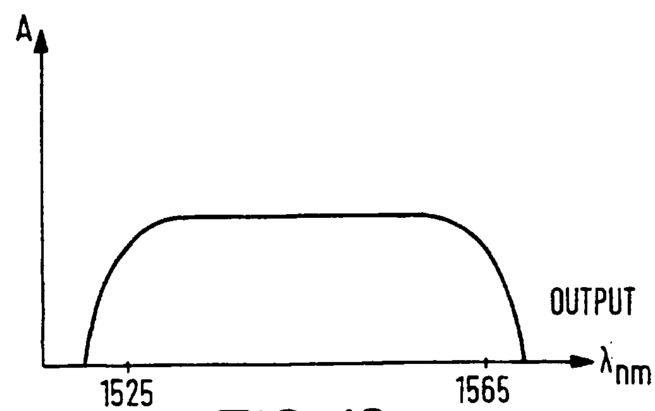


FIG. 16c

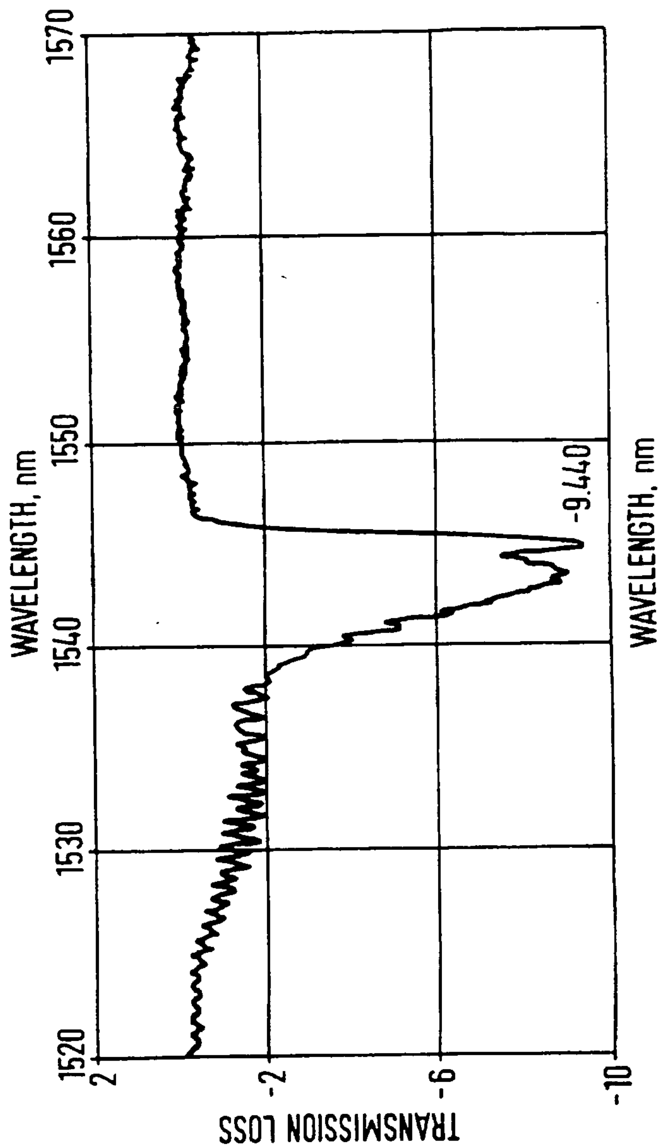

WAVELENGTH, nm
1520
1530
1540
1550
1560
1570
TRANSMISSION LOSS
2
-2
-6
-10
-9.440
WAVELENGTH, nm

FIG. 18

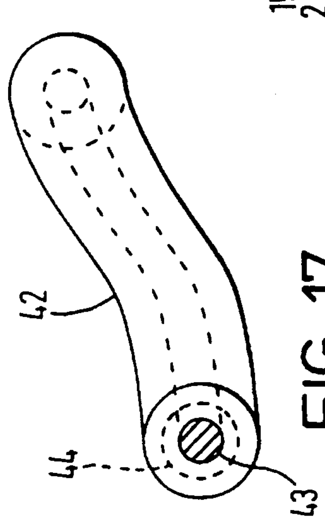

42
44
43

FIG. 17